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**P.H. BRODEUR AND E.L. LEWIS, JR.**

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P.H. Brodeur and E.L. Lewis, Jr.

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# Ultrasonic Characterization of Forming Fabrics

Pierre H. Brodeur and Eddie L. Lewis, Jr.

Engineering and Paper Materials Division,  
Institute of Paper Science and Technology, Atlanta, GA

**ABSTRACT** Nondestructive ultrasonic testing techniques are applied to the characterization of paper machine forming fabrics. A dry-contact, in-plane ultrasonic method is used to determine the velocity of longitudinal elastic waves propagating along the machine and crossmachine directions of forming fabric specimens. Two out-of-plane ultrasonic techniques, a dry-contact method and an immersion method, are used to evaluate the velocity and apparent velocity of thickness direction longitudinal elastic waves, respectively. Stiffness properties are computed from velocity measurements. Correlations between known parameters of forming fabrics and results gathered in this study are examined.

## KEYWORDS

Forming fabrics

Wires

Evaluation

Ultrasonics

Sound velocity

Elastic stiffness properties

Paper formation on the wet end of paper machines is achieved through the use of rotating drainage screens or forming fabrics. These materials, commonly called wires, are made of interlaced synthetic strands.<sup>1,2,3</sup> They serve two basic purposes: to retain and support pulp fibers while effectively draining excess water. With the increased use of high-speed paper machines and higher expectations regarding paper formation, the design of forming fabrics becomes more and more critical. In that regard, a better understanding of mechanical properties could be a significant factor toward an improved design. Also, one could argue that these properties could relate more effectively to desirable paper mechanical and physical properties. As an exploratory approach to the nondestructive evaluation of forming fabric mechanical properties, ultrasonic stiffness measurements were gathered

along the machine direction (MD), crossmachine direction (CD) and thickness direction (ZD).

Ultrasonic sensing methods have been used in the past to investigate web formation, pulp suspension flow and drainage characteristics of forming fabrics, during the normal operations of paper machines.<sup>2,4,5,6</sup> However, it appears that stiffness properties of forming fabrics have not been studied using appropriate ultrasonic instrumentation in the laboratory. At first glance, the task is not easy because forming fabrics are inhomogeneous materials. However, the development of specialized ultrasonic techniques aimed at determining elastic stiffness properties of paper materials simplifies it. The present work concerns the applicability of these techniques to forming fabrics.

More precisely, a dry-contact, in-plane ultrasonic instrument was used to evaluate longitudinal sound velocity measurements along machine and crossmachine directions, respectively. MD and CD specific stiffnesses, MD and CD extensional stiffnesses, and MD and CD elastic stiffness constants ( $C_{11}$  and  $C_{22}$ ) were inferred from these measurements. Then, a dry-contact, out-of-plane method was used to determine the thickness direction longitudinal sound velocity, from which the ZD specific stiffness and elastic stiffness constant  $C_{33}$  were obtained. Finally, an immersion technique was used to evaluate the ZD apparent sound velocity of specimens immersed in water.

Basic concepts of nondestructive ultrasonic characterization are first reviewed. Then, the experimental methodology is described. Measurements and results are next reported and discussed for four fabric specimens, followed by a conclusion.

## **Background: Ultrasonic Stiffness Testing**

Even though forming fabrics are highly inhomogeneous materials, one can assume that they behave as elastic materials with homogeneous and uniform properties along machine and crossmachine directions. This is a direct consequence of the warp (MD) and shute (CD) strands which can be considered as elastic materials. Moreover, assuming that the paper- and machine- side ZD properties do not vary significantly for monolayer fabrics, such fabrics can be considered as orthotropic materials, i.e., materials for which properties are symmetric with three mutually perpendicular directions (MD, CD and ZD). Using the same argument, individual layers of multilayer fabrics can also be considered as orthotropic materials.

The effective homogeneity, uniformity and orthotropy of forming fabrics enable the determination of elastic stiffness components according to the generalized Hooke's law for elastic materials. These components can be obtained indirectly from appropriate elastic wave velocity measurements. This is achieved through the process of producing and detecting cyclic mechanical vibrations or sound waves at ultrasonic frequencies, i.e., frequencies above the audible range ( $> 20$  kHz).

Defining the elastic stiffness as  $C$  along an arbitrary wave propagation axis, this quantity relates to the material density,  $\rho$ , and the wave sound velocity,  $v$ , in the following manner:

$$C = \rho v^2 \quad (1)$$

A useful parameter independent of the density is the specific stiffness,  $C/\rho$ , which corresponds to the square of the velocity. The extensional stiffness is another parameter of interest. It relates to the product of the basis weight and the square of the velocity. Thus, the extensional stiffness is thickness independent.

Restricting the scope of the study to the propagation of longitudinal waves, i.e. waves in which the particle displacement is parallel to the direction of propagation, the normal elastic stiffness components along the principal axes are:

$$C_{11} = \rho(v_{1,x})^2 \quad (2)$$

$$C_{22} = \rho(v_{1,y})^2 \quad (3)$$

$$C_{33} = \rho(v_{1,z})^2 \quad (4)$$

where  $v_{1,x}$ ,  $v_{1,y}$ , and  $v_{1,z}$  are the longitudinal velocities along the x-axis (MD), y-axis (CD) and z-axis (ZD), respectively. The MD/CD ratio,  $(v_{1,x}/v_{1,y})^2$ , provides a simple means of determining the degree of in-plane anisotropy.

Equations are available to relate the normal elastic stiffness constants, Poisson's ratios (Poisson's ratio: ratio of the strain in the lateral direction to the strain in the axial direction), and normal elastic moduli (Young's moduli).<sup>7</sup> Young's moduli can be determined directly from destructive tensile testing. The use of shear waves (vibrations parallel to the

propagation axis) to determine Poisson's ratios was not accomplished in this work. Hence, Young's moduli, indirectly predicted from ultrasonic measurements, were not obtained.

## Experimental Methodology

### In-plane Investigation

A schematic of the dry-contact, in-plane ultrasonic setup used for the determination of  $v_{l,x}$  and  $v_{l,y}$  is shown in Fig. 1.<sup>8</sup> In-plane velocity measurements are obtained by using a pair of small, polarized bimorph transducers (a transmitter and a receiver) in direct contact with the forming fabric's top surface (paper-side). It is assumed that plate waves (lamb's waves) propagate through the strands. No coupling agent is used to improve acoustic coupling conditions. The transducers are mounted on the arm of a robot system (not shown in Fig. 1). In this manner, they can be translated to allow velocity measurements at various locations on the specimen. Also, they can be rotated to allow measurements at different angular positions with respect to machine direction (e.g., machine and crossmachine directions).

A 80 kHz, one-cycle sine wave is used to excite the transmitter. As indicated in Fig. 1, the receiver can be displaced along the propagation axis with respect to the transmitter. This enables the successive detection of two ultrasonic pulses: the so-called near and far transducers' separation distance pulses. The two-pulse detection approach provides velocity measurements, which are independent of the receiver's intrinsic properties and the measurement circuit delay time. A digital oscilloscope and a computer are used to capture and process pulses, respectively. The sound velocity is given by

$$v = (d_2 - d_1) / (t_2 - t_1) \quad (5)$$

where  $d_1$  and  $d_2$  are the separation distances;  $t_1$  and  $t_2$  are the corresponding pulse traveling times. While  $d_2 - d_1$  is a known constant (5 cm), the time difference  $t_2 - t_1$  is accurately determined by using a cross-correlation technique.

Because of the large percentage open area for forming fabrics, satisfactory dry-contact coupling is not easily granted. In order to improve the signal-to-noise ratio, the transmitter excitation voltage was set to 100 V (10 V is a typical Fig. for paper materials). During the

course of preliminary experiments, it was found that meaningful velocity measurements were obtained along the MD and CD axes only, i.e., along the warp and shute strand directions.

### Out-of-plane Dry-contact Testing

A dry-contact, ultrasonic technique developed for the characterization of paper out-of-plane longitudinal stiffness properties was used to determine  $v_{l,z}$ .<sup>9</sup> A schematic of the experimental setup is presented in Fig. 2. The through-transmission arrangement uses a pair of neoprene-faced broadband PVDF transducers operated at 1 MHz. The active area diameter of the transducers is 25 mm. The loading pressure is 50 kPa. Assuming that the fabric thickness,  $h$ , is obtained by evaluating the displacement of one transducer with respect to the other, the ZD longitudinal velocity is calculated from the ratio of the thickness to sound traveling time in the fabric, i.e.,

$$v_{l,z} = h / t_h \quad (6)$$

Pulse recording and processing using the out-of-plane, dry-contact technique is carried out in a manner similar to in-plane testing.

The use of soft neoprene layers enhances dry-contact coupling conditions. Consequently, measurements are less sensitive to surface roughness. Thickness evaluation using soft rubber platens leads to the determination of the soft-platen thickness.<sup>10</sup> When metal platens are used, the thickness is defined as the hard-platen thickness.

### Out-of-plane Immersion Testing

Fabrics were also tested in water using an immersion ultrasonic technique. Since air voids in the fabrics are then filled with water, an apparent out-of-plane sound velocity is determined. A priori, this velocity should not be related to the velocity obtained under dry-contact coupling. Fig. 3 shows a schematic of the water tank setup. Two immersion, piezoelectric ceramic transducers mounted in a transmission mode are used to emit and receive pulses. Their resonant frequency and active area diameter are 2.25 MHz and 19 mm, respectively. The specimen is located at an arbitrary position between the transducers. Its surface is perpendicular to the sound propagation axis. Velocity measurements are obtained by successively collecting "reference" and "specimen" pulses, i.e., pulses detected



without and with the specimen in the sound path between the transducers. It can be shown that the apparent velocity  $v_z'$  is

$$v_z' = h / [(t_r - t_s) + h/v_w] \quad (7)$$

where  $t_r$  and  $t_s$  are the "reference" and "specimen" traveling times between the two transducers;  $h$  is the soft-platen thickness;  $v_w$  is the sound velocity in water (1.497 km/s at 25 °C). A procedure analogous to the dry-contact methods is used to record and process pulses.

## Measurements and Results

### Forming Fabric Parameters

Four forming fabric specimens obtained from Atlanta Wire Works were tested. Their specifications, as provided by the company, are reproduced in Table 1. With the exception of specimen A, all fabrics have multilayer designs. The percentage open area is a function of the warp/shute diameter ratio and the number of warp and shute strands. Air permeability corresponds to the rate of air flow through the strands. The fiber support index (FSI) is a property relating fabric parameters to the ratio of the mean fiber length / average number of supports per fiber.<sup>3</sup> Due to large tension requirements in the machine direction, forming fabrics are designed in such a way that the MD elastic modulus is larger than the CD modulus. Tensile testing is typically limited to the determination of the MD elastic modulus and the Poisson's ratio  $\nu_{yx}$ .

Additional parameters, such as the hard-platen and soft-platen thicknesses, roughness ratio, basis weight, and soft-platen apparent density are presented in Table 2. The roughness ratio is defined as the difference between the hard-platen and soft-platen thicknesses, divided by the soft-platen thickness. The soft-platen apparent density corresponds to the basis weight divided by the soft-platen thickness. It is denoted that the soft-platen thickness is generally lower than the hard-platen thickness by more than 20%. Design A has a rougher surface than designs B, C, and D. This observation is further appreciated in Fig. 4: the data point for design A does not follow the linear trend between the soft-platen and hard-platen thicknesses.

## In-plane Results

Using the in-plane ultrasonic technique previously described, MD and CD longitudinal velocities were collected at 10 different locations on the paper side of each specimen. MD and CD velocities, MD and CD extensional stiffnesses,  $C_{11}$  and  $C_{22}$ , and the MD/CD ratio are shown in Table 3. One must be careful in the interpretation of the results for specimens B, C and D because plate wave velocity measurements are most likely to be different for each layer. This was not explicitly verified.

Nevertheless, one can examine the behavior of the CD extensional stiffness as a function of the MD extensional stiffness. This is displayed in Fig. 5. As one might expect from MD tension requirements, the CD extensional stiffness is systematically lower than the MD extensional stiffness. Lack of measurement repeatability for design A is attributed to the large roughness ratio for this specimen (see Table 2). As indicated by the MD/CD ratio in Table 3, in-plane anisotropy is minimum for design C and maximum for design A.

Fig. 6 represents the plot of the MD extensional stiffness as a function of the MD elastic modulus, obtained from tensile testing (see Table 1). Excellent agreement for design A is attributed to the fact that design A is monolayer. This observation supports the hypothesis that paper-side measurements might be misleading for multilayer fabrics. Excellent agreement for design A suggests that nondestructive ultrasonic stiffness measurements might be used to predict tensile measurements. The plot of  $C_{22}$  versus  $C_{11}$  is depicted in Fig. 7. It is of particular interest to note that  $C_{22}$  appears to be inversely linearly related to  $C_{11}$ . Considering the limited number of tested specimens, this relationship may be fortuitous.

## Out-of-plane Results

Analyzing first the dry-contact results which are reported in Table 4, it is seen that the ZD velocity for fabric A is large when compared to other fabric velocities. This is an indication that the fabric A is a relatively stiffer material in the thickness direction. This may somehow be related to the MD and CD strand diameters, which are larger for this specimen. It was not possible to correlate the ZD velocity, ZD specific stiffness and  $C_{33}$  to other fabric properties. Implications of the velocity dependency upon multiple layers for specimens B, C and D would require further investigation.

The last set of data obtained from immersion testing experiments is also presented in Table 4. It is seen that the ZD apparent velocity does not correlate to the ZD velocity. Because the sound velocities in polyester and nylon (solid phases) are larger than the sound velocity in water (liquid phase), it is no surprise to observe that the ZD apparent velocity systematically exceeds the sound velocity in water (approximately 15%). The ZD apparent specific stiffness plotted against the fiber support index is shown in Fig. 8. This graph suggests an inverse relationship between these parameters for designs A, B, and D (polyester fabrics).

## Conclusion

Nondestructive ultrasonic testing is an important tool regarding material characterization. Exploratory results reported in this paper indicate that ultrasonic techniques can be used to evaluate elastic stiffness properties of forming fabrics. However, much remains to be done as measurements were not performed on a systematic basis. It is clear that a study involving fully characterized specimens is necessary to assess the potential of ultrasonic testing. Constants  $C_{11}$ ,  $C_{22}$  and  $C_{33}$  might reveal their usefulness in the context of mechanical property optimization. It might be of particular interest to investigate the behavior of  $C_{11}$  as a function of the loading tension.

This work was limited to the study of longitudinal waves and the determination of the normal elastic stiffness constants. In-plane and out-of-plane shear measurements could be performed to determine the Young's moduli, Poisson's ratios and shear moduli.

The ZD apparent velocity, which is obtained in a water tank, might be an excellent indicator of insufficient fabric cleansing during paper machine normal operations. On-line monitoring of this property could be achieved by the use of transducers immersed in fluid-filled rubber wheels in contact with the rotating fabric. This measurement scheme is currently implemented for on-line monitoring of paper out-of-plane elastic stiffness properties.<sup>11</sup> Continuous determination of the paper-side sound reflection coefficient, if successful, might provide new insights regarding paper formation.

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FABRIC PARAMETERS / DESIGNS	A	B	C	D
Material	Polyester	Polyester	Nylon	Polyester
MD Strands/in X CD Strands/in	46 X 39	164 X 119	149 X 97	71 X 60
Number of Layers	1	2	2	3
MD Strand Diameter (mm) (Warp)	0.350	0.160	0.170	—
Top Layer	—	—	—	0.119 X 0.173
Bottom Layer	—	—	—	0.190 X 0.381
CD Strand Diameter (mm) (Shute)	0.350	0.188	—	—
Top Layer	—	—	0.221/0.130	0.163
Middle Layer (CD Binder)	—	—	—	0.128
Bottom Layer	—	—	0.256	0.350
% Open Area	17%	Unavailable	Unavailable	32%
Air Permeability (m <sup>3</sup> /min)	16.3	9.5	16.1	16.4
Fiber Support Index (-)	67	104	104	127
MD Elastic Mod. (N/m x 10 <sup>6</sup> )	2.01	1.44	1.66	1.54
Poisson's ratio $\nu_{yx}$ (-)	0.52	0.08	0.33	0.53

Table 1. Forming fabric specifications as provided by Atlanta Wire Works.

BASIC PROPERTIES / DESIGNS	A	B	C	D
Hard-platen Thickness ( $\mu\text{m}$ )	802	641	748	1024
Soft-platen Thickness ( $\mu\text{m}$ )	584	529	604	802
Roughness Ratio (-)	0.37	0.21	0.24	0.28
Basic Weight ( $\text{kg/m}^2$ )	0.474	0.424	0.385	0.463
Soft-platen Apparent Density ( $\text{kg/m}^3$ )	812	802	637	594

Table 2. Additional parameters of forming fabrics.

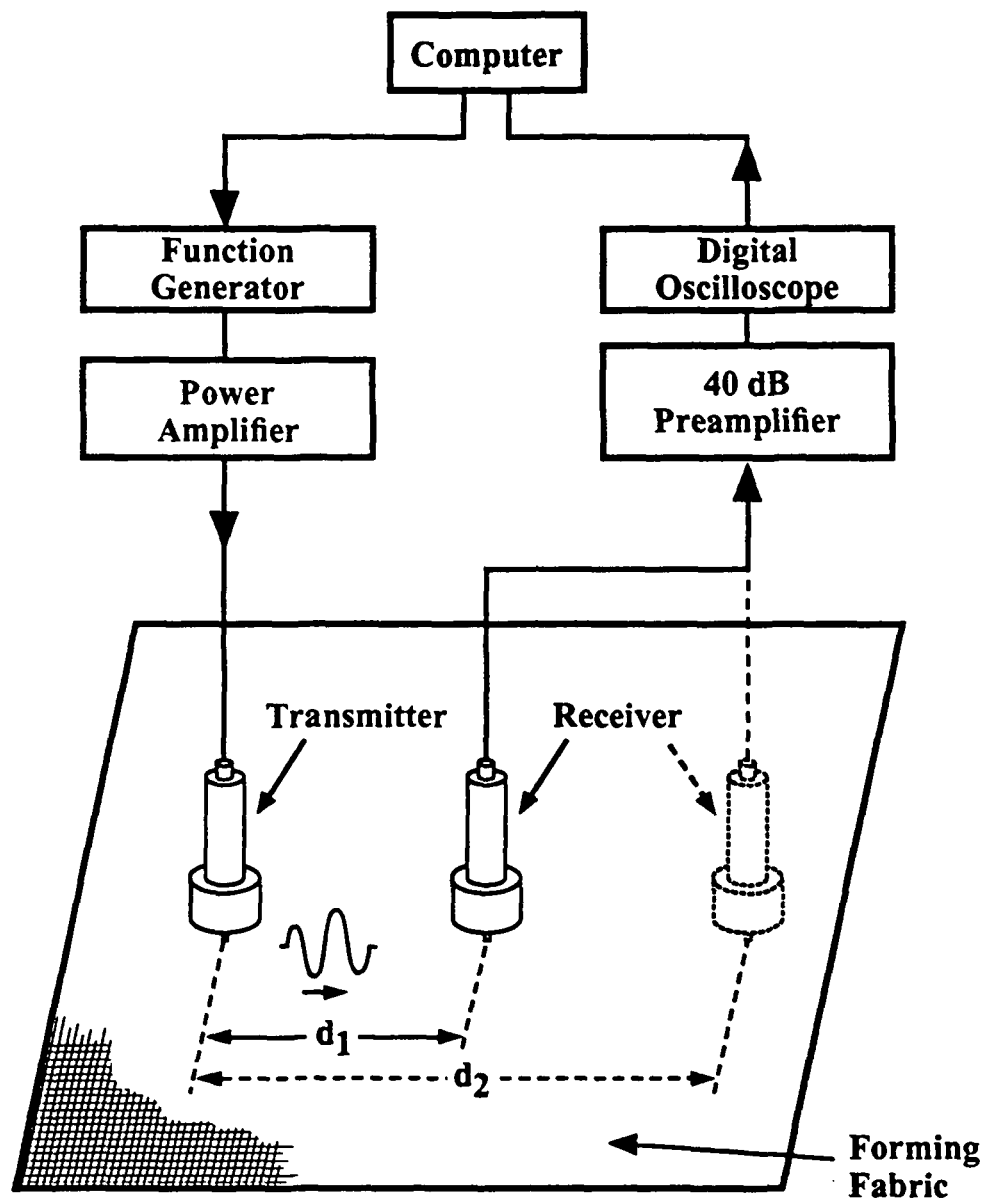
MD AND CD PROPERTIES / DESIGNS	A	B	C	D
MD Velocity (km/s)	2.04	1.65	1.52	2.17
CD Velocity (km/s)	0.55	0.83	1.09	0.94
MD Extens. Stiff. (N/m X 10 <sup>6</sup> )	1.97	1.15	0.89	2.18
CD Extens. Stiff. (N/m X 10 <sup>6</sup> )	0.14	0.29	0.46	0.41
C <sub>11</sub> (Gpa)	3.38	2.19	1.46	2.80
C <sub>22</sub> (Gpa)	0.24	0.56	0.75	0.52
MD/CD Ratio	14.1	4.0	1.9	5.3

Table 3. MD and CD properties as obtained from in-plane ultrasonic measurements.

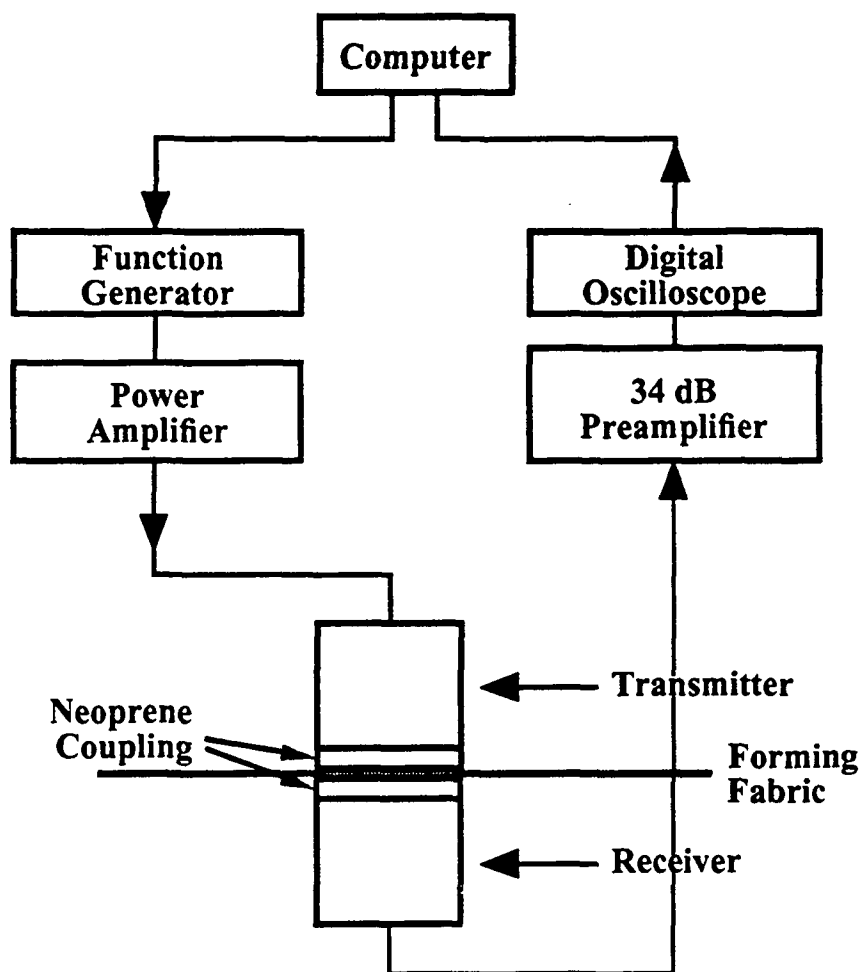
ZD PROPERTIES / DESIGNS	A	B	C	D
ZD Velocity (km/s)	2.45	1.04	0.92	0.97
ZD Specific Stiffness (km/s) <sup>2</sup>	6.02	1.07	0.84	0.95
C <sub>33</sub> (kPa)	4.89	0.86	0.54	0.56
ZD Apparent Velocity (km/s)	1.82	1.72	1.62	1.65
ZD App. Spec. Stiffness (km/s) <sup>2</sup>	3.31	2.96	2.62	2.72

Table 4. ZD properties determined using out-of-plane, dry-contact and immersion techniques.

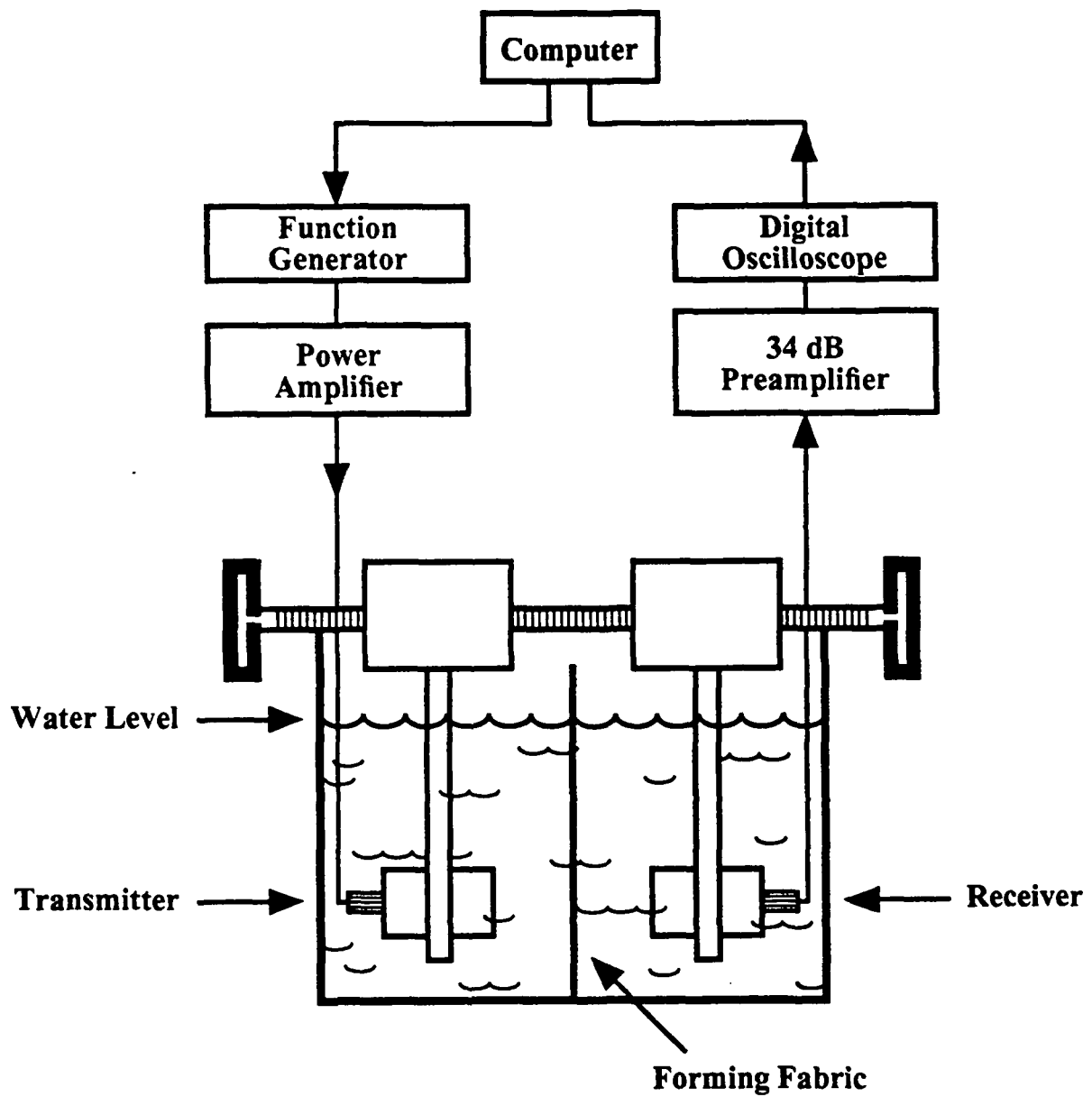




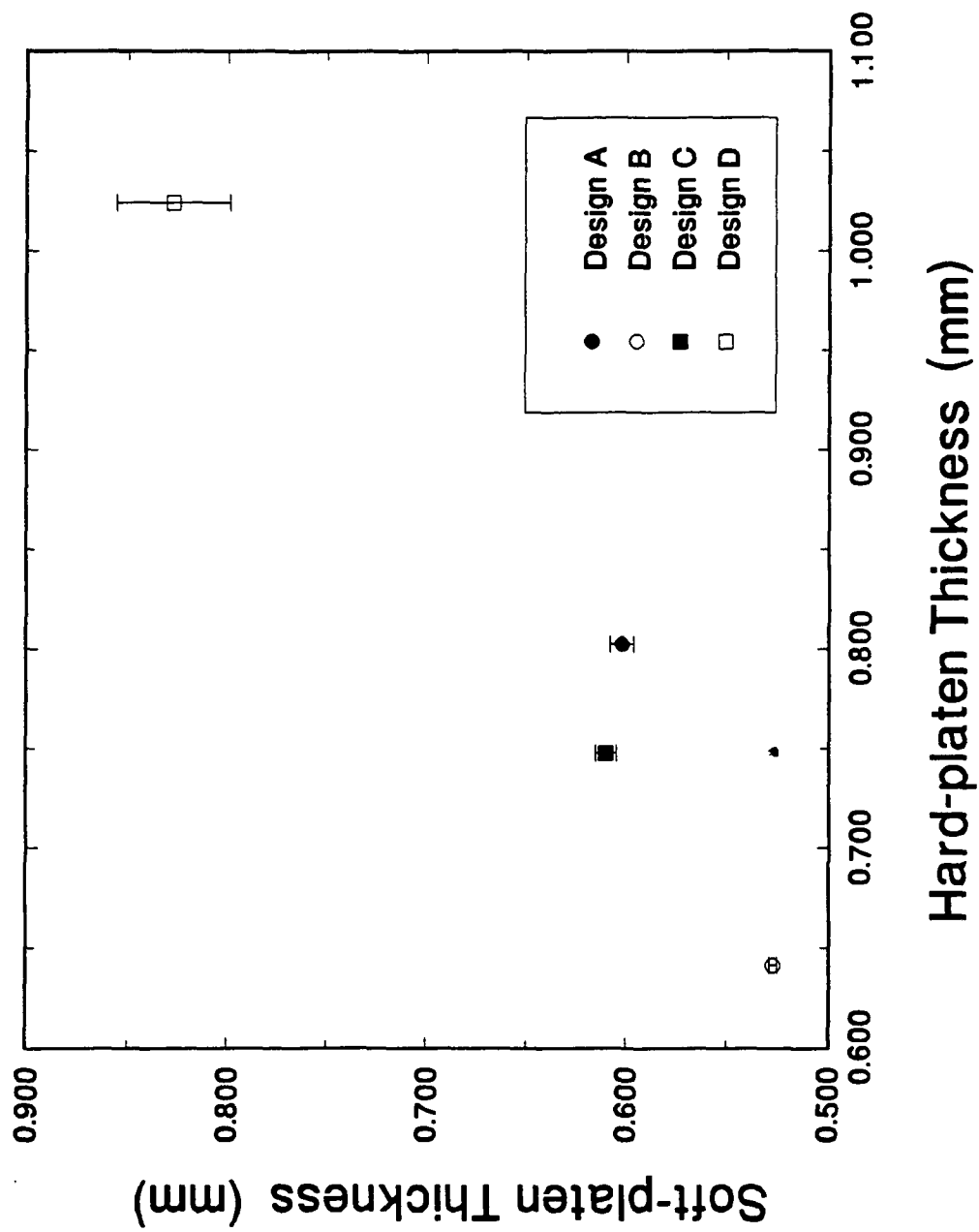
1. Schematic of the dry-contact, in-plane ultrasonic measurement technique.



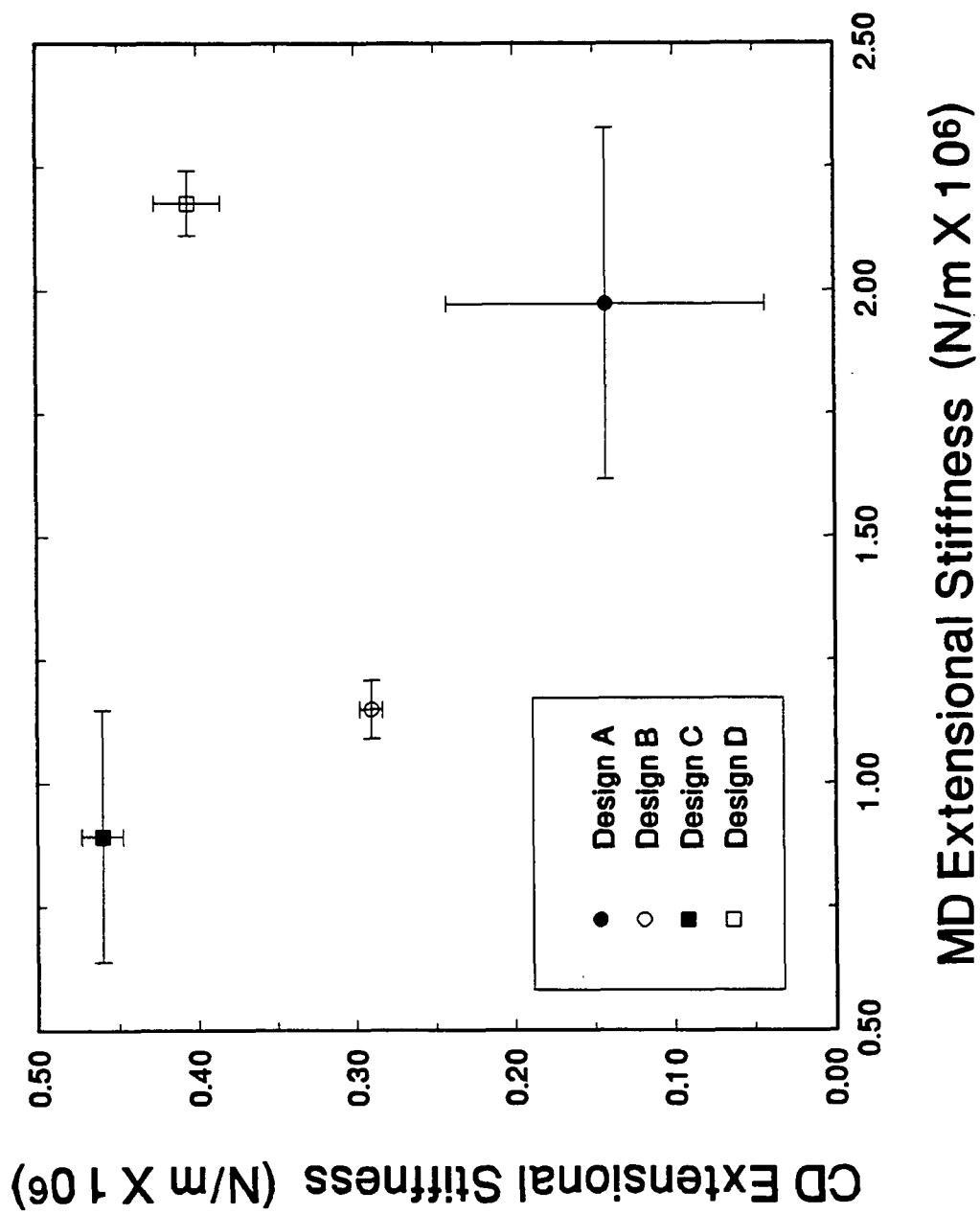
2. Schematic of the dry-contact, out-of-plane ultrasonic measurement technique.



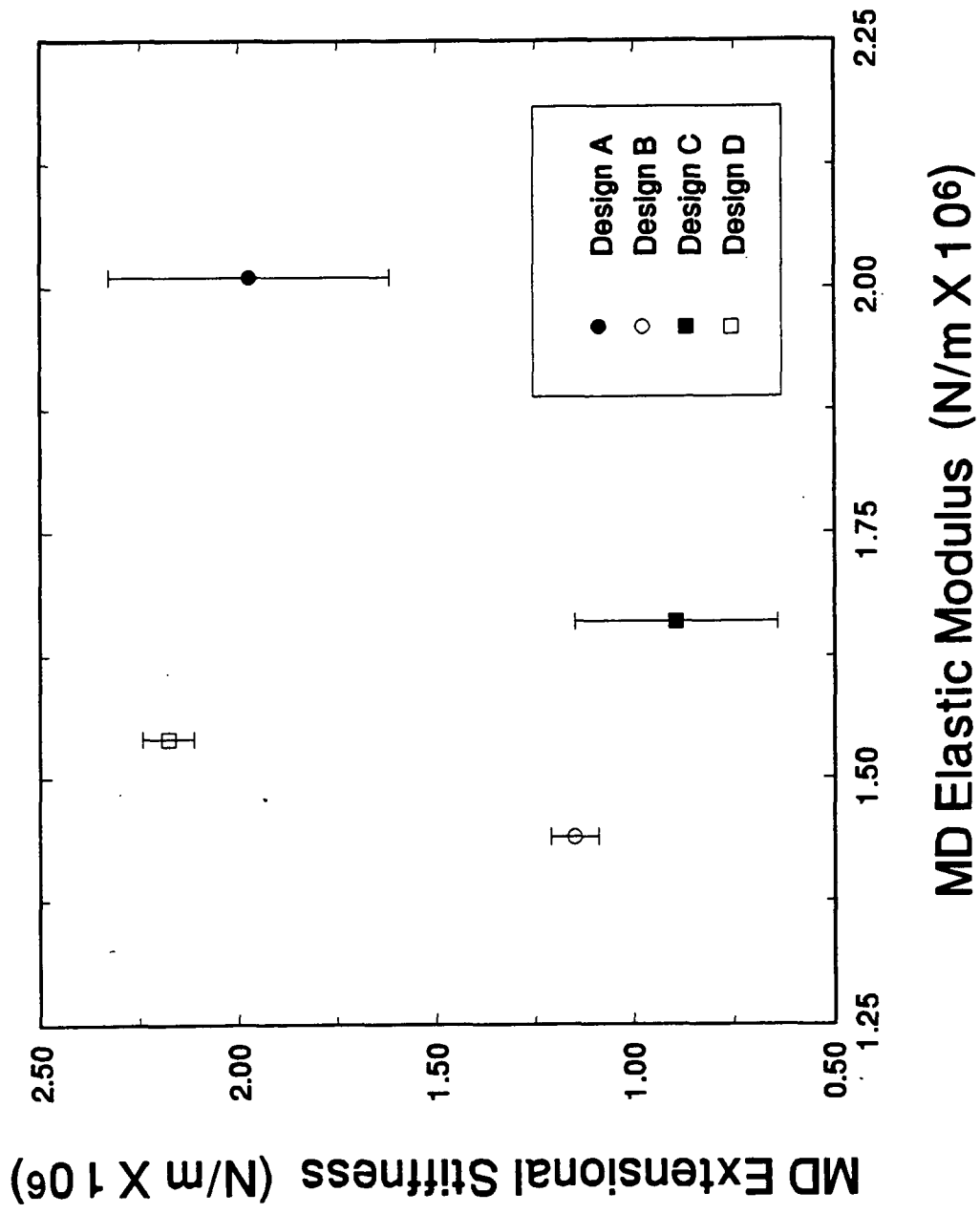
3. Schematic of the immersion setup for out-of-plane ultrasonic measurements.



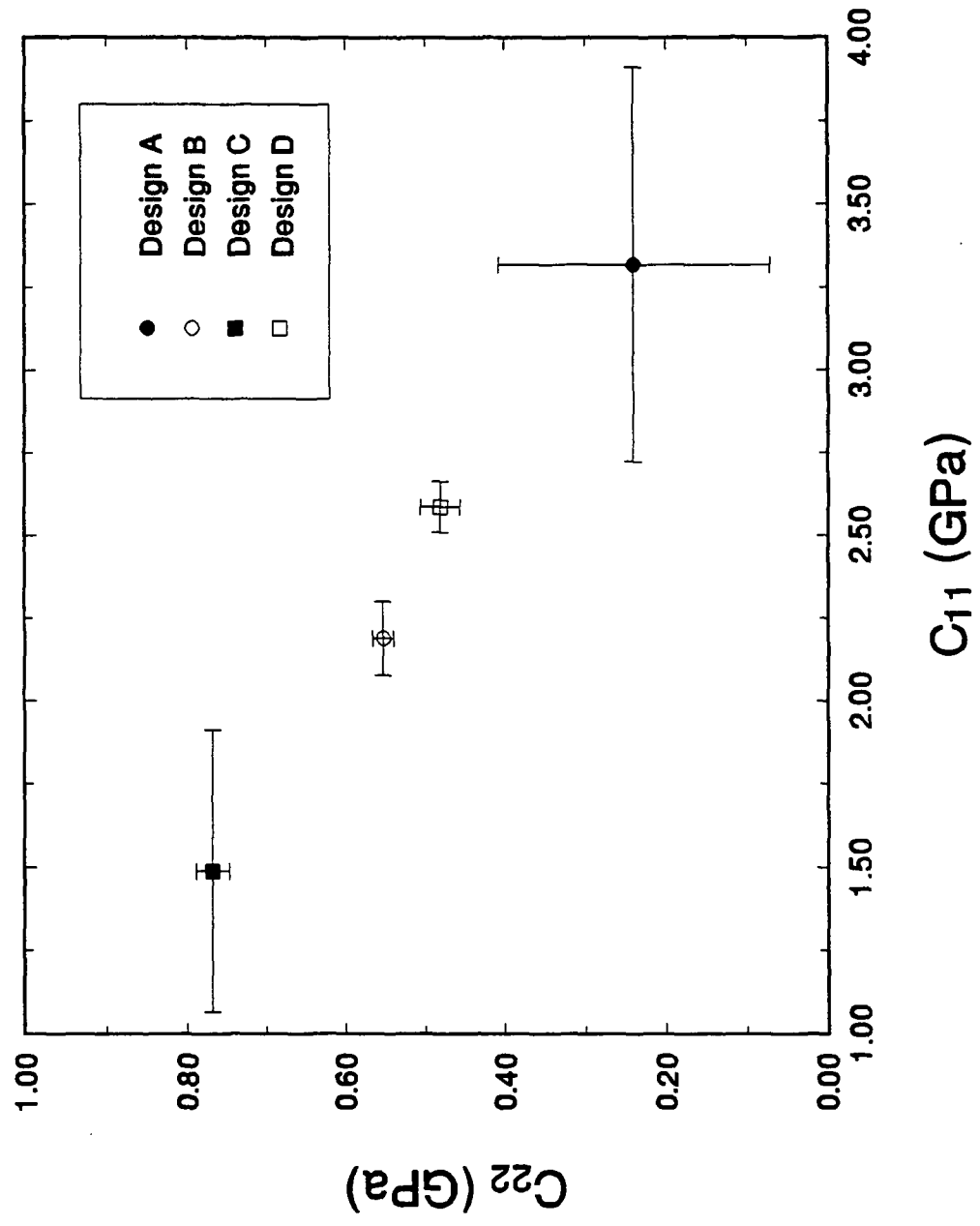
4. Plot of the soft-platen thickness as a function of the hard-platen thickness. Standard deviations are reported as error bars.



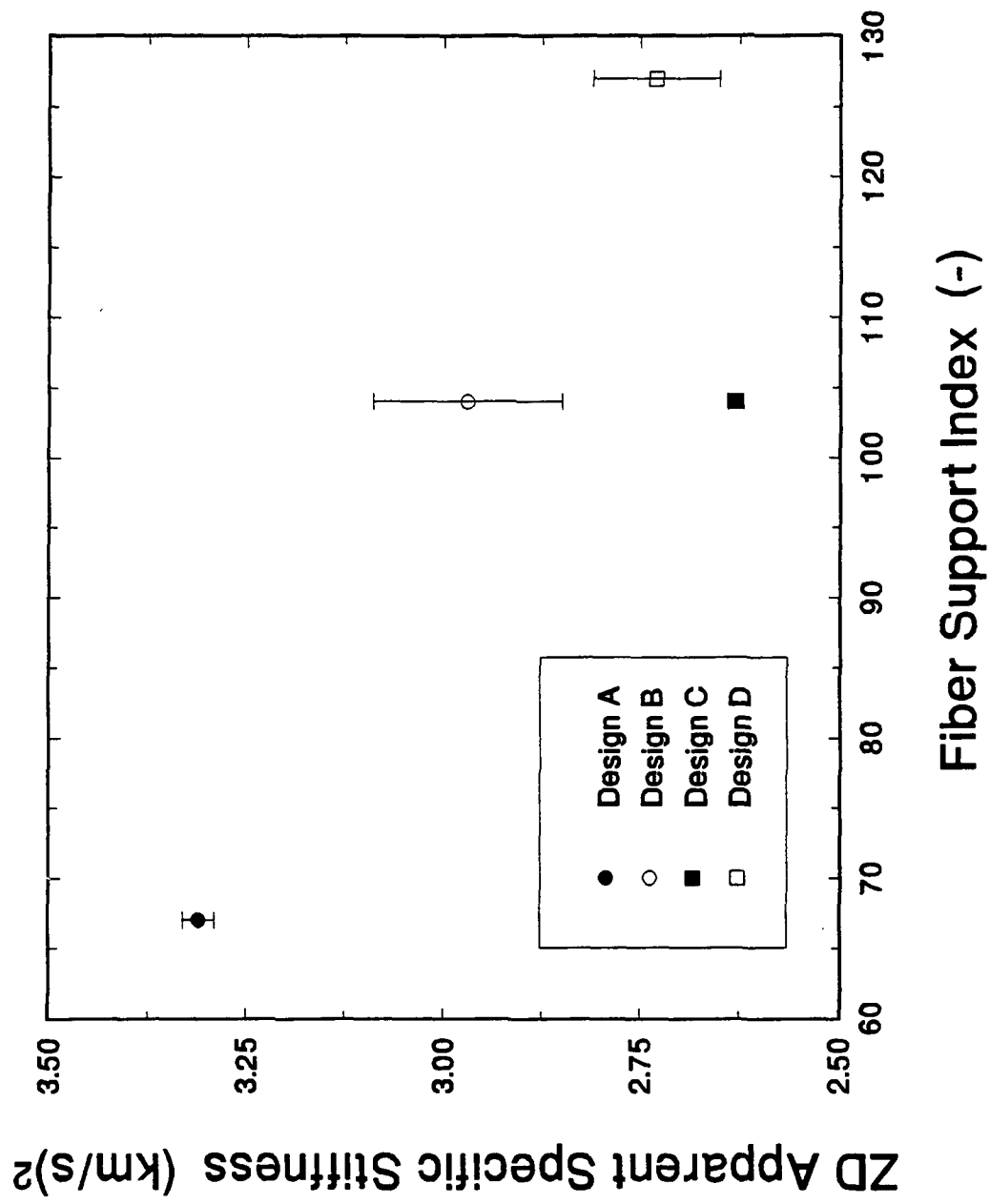
5. Plot of the CD extensional stiffness versus the MD extensional stiffness.



6. Plot of MD extensional stiffness as a function of the MD elastic modulus.



7.  $C_{22}$  plotted against  $C_{11}$ .



8. ZD apparent velocity versus fiber support index.